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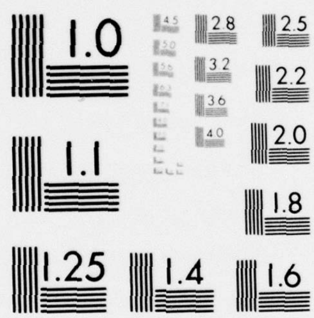

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PROGRESS IN NUMERICAL FLUID DYNAMICS AT DTNSRDC

Joanna W. Schot

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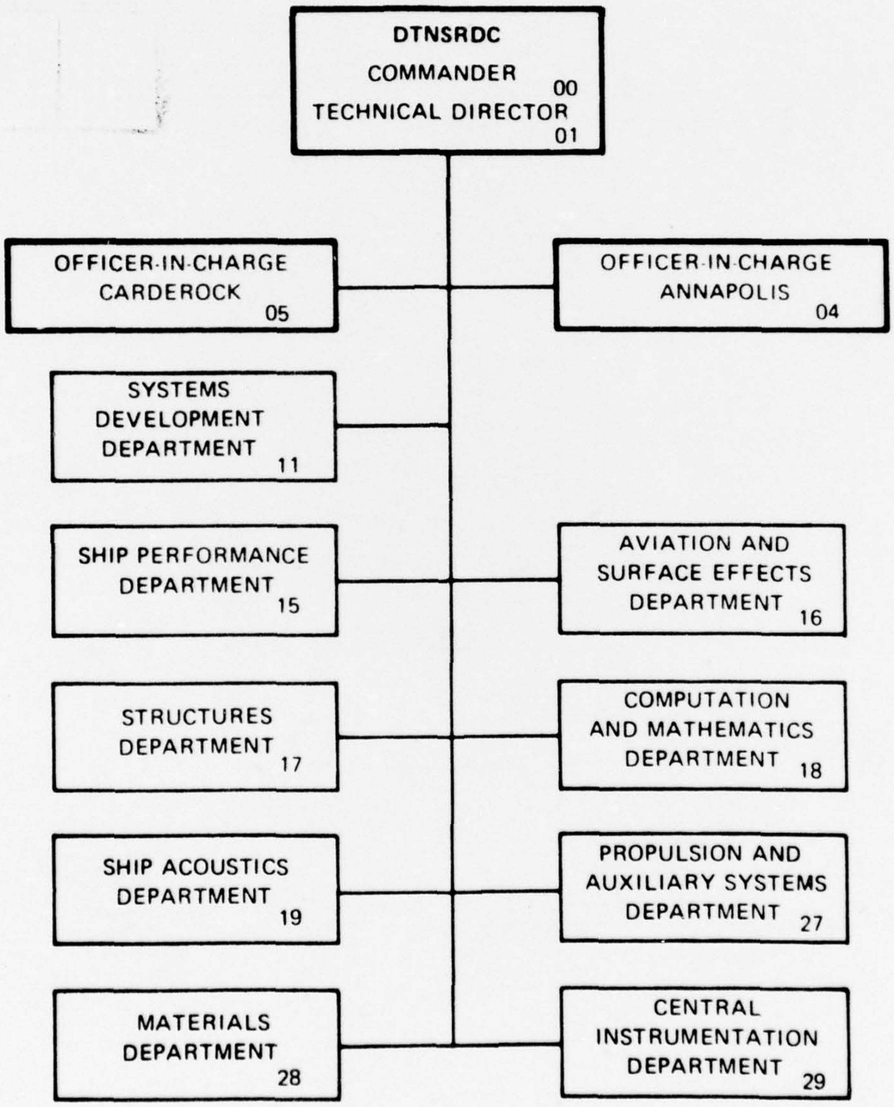

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Highlights are presented of some of the work in numerical fluid dynamics which has recently been completed at the David W. Taylor Naval Ship Research and Development Center (DTNSRDC). This work involves the development of new numerical and computer techniques for solving both viscous and inviscid fluid flow problems, which are pertinent to the research goals of this Data Exchange Agreement. References are also made to some of the related work being done under contract for the Center. The topics discussed include free surface → next page

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potential flow, viscous and interacting flows, and fluid-structure interactions. Combinations of spectral, finite-difference, and finite-element methods are employed in the numerical approaches. Applications of these methods to the performance analysis of air-cushion vehicles, conventional ships, rotating plates, and circulation-controlled airfoils are briefly discussed.

A

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PROGRESS IN NUMERICAL FLUID DYNAMICS AT DTNSRDC

by

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ABSTRACT

Highlights are presented of some of the work in numerical fluid dynamics which has recently been completed at the David W. Taylor Naval Ship Research and Development Center (DTNSRDC). This work involves the development of new numerical and computer techniques for solving both viscous and inviscid fluid flow problems which are pertinent to the research goals of this Data Exchange Agreement. References are also made to some of the related work being done under contract for the Center. The topics discussed include free surface potential flow, viscous and interacting flows, and fluid-structure interactions. Combinations of spectral, finite-difference, and finite-element methods are employed in the numerical approaches. Applications of these methods to the performance analysis of air-cushion vehicles, conventional ships, rotating plates, and circulation-controlled airfoils are briefly discussed.

1. Introduction

This paper highlights some of the work in numerical fluid dynamics which has recently been completed and is being further developed at DTNSRDC. As the name of the Center indicates, our research is directed toward the analysis and solution of ship performance problems and the design of improved naval ships. The word "ship" is used in the broadest sense to encompass not only conventional designs but also advanced-concept vehicles such as hydrofoil craft, twin-hull configurations, and surface-effect ships. Thus, ship hydrodynamics problems form a large part of our numerical work in fluid dynamics. However, many important problems

involving the aerodynamic properties of higher-speed surface ships, air-cushion vehicles, and carrier-based aircraft must also be solved. Fortunately, from the numerical point of view, techniques developed to solve aerodynamic problems can often be applied to hydrodynamics problems, and conversely. It is the aim of this paper to call attention to recently developed numerical methods and computer techniques which can be further exploited to solve diverse problems pertinent to the research goals of this Data Exchange Agreement. The areas of research to be discussed in the following sections are potential flow with free surface conditions, viscous-inviscid interacting flows, viscous flows based on the full Navier-Stokes equations, and fluid-structure interactions.

2. Free Surface Potential Flow

The problem of computing the non-lifting potential flow past an arbitrary three-dimensional body has been solved by the source-sink method of Hess and Smith [1], developed under contract for DTNSRDC. This method is regularly used in the process of solving aerodynamic and hydrodynamic problems at the Center, especially the improved programs developed by Dawson [2] and Dawson and Dean [3] known as the XYZ Potential Flow Program with various options. These improved programs compute on-body streamlines for input to boundary layer programs, use a more accurate source calculation which reduces leakage for internal flows, and provide special input-checking for accurate definition and paneling of the body surface. However, these popular methods cannot handle potential flow problems with a free surface, such as the wave motion at an air-sea interface. Since naval ships operate in, slightly above, or below this interface, methods for solving potential flow problems with free surface conditions are important. In the past few years various methods, both analytical and numerical, for solving these problems in two and three spatial dimensions have been investigated under the Center's Numerical Ship Hydrodynamics Program. The Proceedings of the First International Conference on Numerical Ship Hydrodynamics, sponsored by DTNSRDC in October 1975, contain many papers on this subject including a review paper by C. von Kerczek [4]. Two of these papers on the moving surface pressure distribution problem and the thin ship problem are summarized below.

a) Moving Surface Pressure Distribution

Haussling and Van Eseltine [4a] have developed a combination of finite-difference and spectral (Fourier series) methods to solve transient potential flow problems with both linear and nonlinear free surface conditions. The basic problem which they solved is the flow generated by a pressure disturbance $p(x,z,t)$ moving across a free surface denoted by $y = \eta(x,z,t)$, where t is time and an (x,y,z)-coordinate system is used. Figure 1 illustrates the two-dimensional version of the computational region and the boundary conditions employed. The coordinate system moves with the disturbance. The two-dimensional initial/boundary value problem in the moving reference frame with nonlinear free surface conditions is written in the form

$$\phi_{xx} + \phi_{yy} = 0 \qquad -\ell < x < \ell, \ -d < y < \eta \tag{1}$$

$$\eta_t = -U\eta_x - \phi_x\eta_x + \phi_y \quad \text{at} \quad y = \eta \tag{2}$$

$$\phi_t = -U\phi_x - \frac{1}{F_r^2}\eta - \frac{1}{2}(\phi_x^2 + \phi_y^2) - \frac{\delta}{F_r^2}p \quad \text{at} \quad y = \eta \tag{3}$$

$$\phi_x = 0 \quad \text{at} \quad x = \pm\ell \tag{4}$$

$$\phi_y = 0 \quad \text{at} \quad y = -d \tag{5}$$

$$\phi = 0, \ \eta = -\delta p \quad \text{at} \quad t = 0 \tag{6}$$

where $\phi(x,y,t)$ is the velocity potential and subscripts x, y, and t denote differentiation with respect to these independent variables. The dimensionless parameters are the Froude number $F_r = U/(g L)$, based on the length of the pressure disturbance L, and $\delta = P/\rho g L$, where U is the speed of the disturbance, g is the gravitational acceleration, ρ is the constant density of the fluid, and P is the maximum surface pressure. The pressure disturbance may be arbitrarily specified. Haussling and Van Eseltine evaluated both a spectral method and a finite-difference method for solving the Laplace equation. For the time-advancement they used an over-all marching scheme which coupled the solution of the Laplace equation with numerical approximations to the time-dependent free-surface

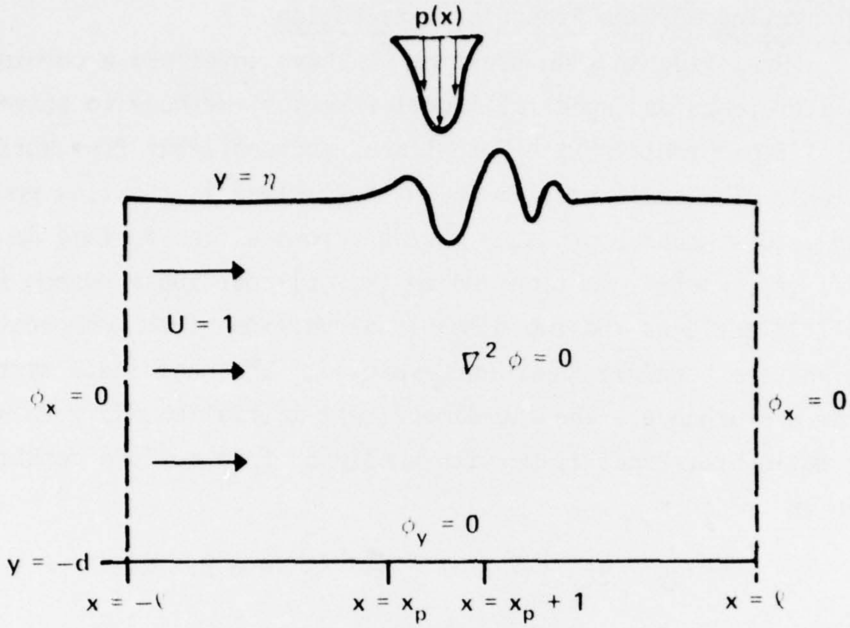

Figure 1. The Two-dimensional Computational Region for the Moving Surface Pressure Distribution Problem.

boundary conditions. For solving three-dimensional problems, the free surface conditions given by Equations (2) and (3) were linearized and replaced by the following expressions which are valid for small wave slopes only

$$\left.\begin{aligned} \eta_t &= -U\eta_x + \phi_y \\ \phi_t &= -U\phi_x - \frac{1}{F_r^2}\eta - \frac{\delta}{F_r^2}p \end{aligned}\right\} \quad \text{at} \quad y = 0 \qquad (7)$$

Based on the favorable results obtained and the experience gained with these approaches, a three-dimensional computer program known as ACVWAVES has been developed by Haussling and Van Eseltine [5] to calculate the unsteady hydrodynamic characteristics of an air-cushion vehicle (ACV) or surface-effect ship (SES). This program uses Fourier series expansions to compute the wave resistance, side force, yawing moment, total power, and wave elevations associated with vehicles moving on arbitrary trajectories over calm or disturbed seas. Computer-generated pictures of the waves

obtained by this program are shown in Figure 2. In this calculation the ACV, which appears as the small square in each frame of the figure, is represented by the following pressure distribution:

$$p(y=0) = \begin{cases} \sin^2(\pi x^*)\ \sin^2(\pi z^*) & 0 \le x^* \le 1 \text{ and } 0 \le z^* \le 1 \\ 0 & \text{otherwise} \end{cases}$$

where a right-handed (x,y,z) coordinate system is used, and (x^*,z^*) denotes the coordinates moving with the ACV. The results, as stated by the authors in [5], indicate that their scheme provides an efficient means for analyzing ACV hydrodynamics. By use of a theory which relates an arbitrary pressure distribution to the surface elevation and the motions of the ACV, the pressure distribution could be adjusted realistically as the ship maneuvers.

b) Thin Ship Problems

Another approach to solving transient three-dimensional potential free surface flow problems has been developed by Ohring [6] and applied to conventional "thin" ships. This work makes use of a very fast finite-difference scheme for solving the Laplace equation which is an outgrowth of earlier research in viscous fluid flow by Lugt and Ohring, who studied the efficiency of various methods for constructing solutions of the Navier-Stokes equations [7]. Using a fourth-order difference operator and thin ship theory, Ohring computed the time-dependent three-dimensional potential flow around a thin ship with linearized free surface conditions. The direct method for solving the system of difference equations is a modified diagonal decomposition technique which makes use of the fast Fourier transform. Ohring's paper [6] gives details of this scheme and the results obtained. Three-dimensional wave patterns generated in a channel by Ohring's THINSHIP computer program are shown from an aerial viewpoint in Figure 3. The time T=3 indicates that the ship has moved upstream a distance equal to three times the length of the ship. The region of computation, which extends farther downstream than shown in the figure, is represented by 129 grid points along the length of the channel, 17 points across half the channel width, and 64 points from the water

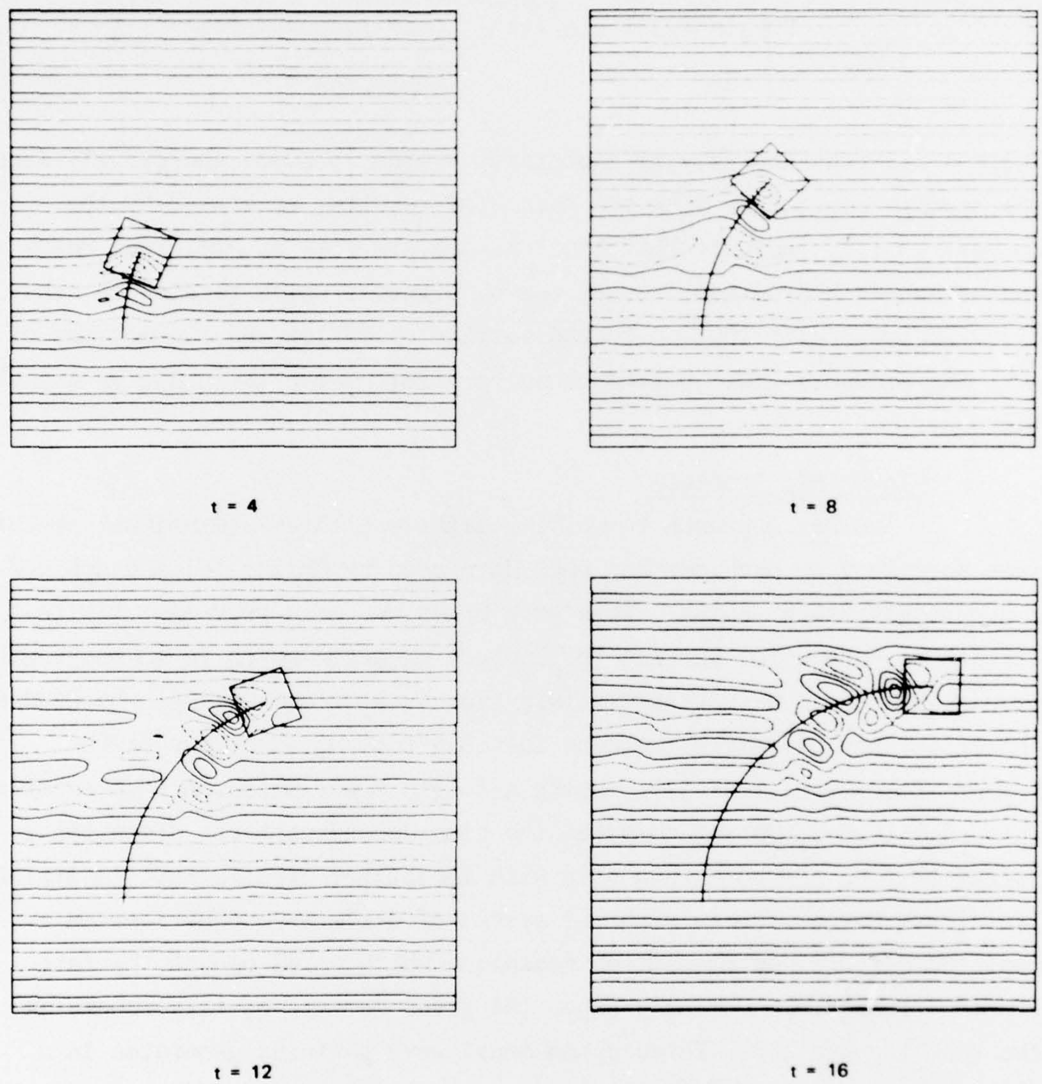

Figure 2. Wave Elevations at Four Successive Times Generated by an ACV Moving Over a Disturbed Area. Negative values (depressions) are represented by broken lines.

surface to the bottom of the channel. This extensive calculation required less than five minutes of computer time on the CDC 6600, and the results compare favorably with patterns generated by ship model experiments.

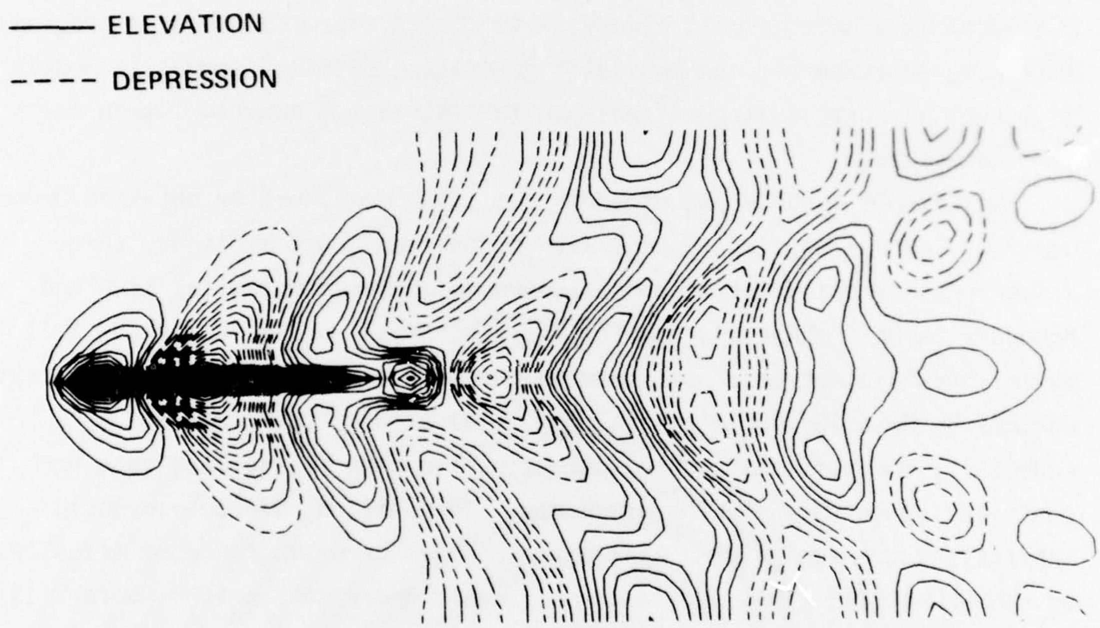

Figure 3. Aerial View of 3-D Waves Generated by a Thin Ship at Time T = 3.0.

3. Viscous and Interacting Flows

In addition to the established methods of applying potential flow and boundary layer theory to compute viscosity-dependent aerodynamic or hydrodynamic characteristics of naval vehicles, more accurate methods which provide flow details are needed for certain types of new design problems. Drag reduction requirements for higher speed helicopters, vertical or short takeoff and landing (V/STOL) aircraft, as well as for faster ships and submarines have made it necessary to obtain improved computer programs, including programs for automatically generating detailed geometric models of actual hardware configurations and the associated numerical mesh for the flow field.

At DTNSRDC methods and programs are being developed or obtained under contract for calculating viscous flow properties about arbitrary three-dimensional or axisymmetric bodies based on improved potential flow and boundary layer techniques, and for two-dimensional bodies using the full Navier-Stokes equations. The more recent work done at the Douglas Aircraft Company by Hess [8] for improving potential flow calculations and by Cebeci [9] for performing three-dimensional boundary layer analyses are contributing to these new developments. In addition, viscous-inviscid interacting transonic flows over airfoils have been studied theoretically at DTNSRDC by Tai [10], [11] and numerically under contract by Dvorak [12]. This numerical work combines potential flow and boundary layer methods in an iterative procedure which calculates interactions between the viscous and inviscid regions and results in the prediction of viscosity dependent aerodynamic forces. However, even these improved methods based on boundary layer theory cannot solve classes of problems involving separated flow regions.

As discussed at the last DEA meeting [13], in order to compute the detailed behavior of viscous flow development and vortex shedding, including the variation in drag, lift, and moment coefficients with time, accurate solutions of the full Navier-Stokes equations are required. For this reason fully viscous flows past two-dimensional bodies at an angle of attack have been studied at the Center by Lugt and Haussling [14] who developed techniques for obtaining numerical solutions of the Navier-

Stokes equations. The comparison of various numerical methods for solving these equations which was carried out by Lugt and Ohring [7] led these authors to solve the difficult problem of flow past rotating plates [15]. In the following paragraphs, recent progress in two of these areas of research will be described; namely, interacting flows over circulation-controlled airfoils and viscous flows past rotating cylinders.

a) Viscous-Inviscid Interacting Flows over Circulation-Controlled Airfoils

An example of the need for improved numerical methods for solving viscous-inviscid interacting flows is the detailed design of the V/STOL X-wing aircraft, an artists conception of which is shown in Figure 4. As described by one of its designers, Robert M. Williams [16], this new aircraft concept, now under development at DTNSRDC and Lockheed Aircraft Corporation, will operate either as a rotary wing high-speed helicopter or as a fixed-wing aircraft. The boundary layer over the airfoils is controlled by using the concept known as reverse velocity blowing in which a thin jet of air is ejected tangentially over the rounded trailing edge of the airfoil. This jet suppresses boundary layer separation and permits the positioning of the rear stagnation point to optimize lift. As pointed out by Williams [16], the technology base for the X-wing concept has been derived from about six years of related circulation control rotor research at the Center and earlier studies in the United Kingdom and the United States.

In order to perform successful circulation control analysis for the X-wing aircraft, accurate numerical methods which can take into account the effects of airfoil curvature and separation are required in addition to wind tunnel experiments. The work of Dvorak [12] and his colleagues has led to a procedure for calculating viscous/potential flow interaction analysis which is a useful numerical tool. Other numerical approaches are under development at the Center for improving the aerodynamic analysis of aircraft equipped with circulation-controlled airfoils.

Figure 4. The Circulation Control X-wing V/STOL Aircraft Concept

b) Rotating Elliptic Cylinders in a Viscous Fluid

Numerical solutions of laminar flow fields around rotating elliptic cylinders in a fluid at rest or in a parallel stream have been obtained by Lugt and Ohring and preliminary results have been published [15]. These authors constructed solutions of the stream function-vorticity formulation of the Navier-Stokes equations using the DuFort-Frankel scheme for the vorticity equation and the Hockney direct method for the Poisson equation. In their recently completed paper [17] the transient period from the abrupt start of the rotation to a later time is investigated by calculating streamlines and equivorticity lines as well as the drag, lift, and moment coefficients. For purely rotating cylinders oscillatory behavior is observed and explained by these authors. Bodies rotating in a parallel stream are studied for two cases: (1) when the vortex developing at the retreating edge of the thin ellipse appears on the upstream side of the edge and (2) when it appears on the downstream side of the edge. The cylinder is assumed to be infinitely long so that a two-dimensional

formulation in elliptical coordinates (η,θ) may be used. For the body rotating in a parallel flow, the dimensionless Navier-Stokes equations are written

$$\frac{\partial\omega}{\partial t} + \frac{1}{h^2}\left[-\frac{\partial}{\partial\eta}\left(\frac{\partial\psi}{\partial\theta}\omega\right) + \frac{\partial}{\partial\theta}\left(\frac{\partial\psi}{\partial\eta}\omega\right)\right] = \frac{2}{Re}\nabla^2\omega \tag{8}$$

$$\nabla^2\psi = \omega, \tag{9}$$

where ω is the vorticity, ψ is the stream function, t is the time, ∇^2 is the Laplacian operator, and $Re = 2aU/\nu$ is the Reynolds number in which a is the focal length of the ellipse, U is the free stream velocity, and ν is the kinematical viscosity. The boundary conditions are:

On the surface of the ellipse $\eta = \eta_1$: $\psi=0$ and $\partial\psi/\partial\eta = 0$

In the outer flow field $\eta = \eta_\infty$: $\frac{1}{h}\frac{\partial\psi}{\partial\theta} = \cos(\theta - t/Ro)$

$$\frac{1}{h}\frac{\partial\psi}{\partial\eta} = \sin(\theta - t/Ro) + \frac{1}{hRo}(\cosh\eta\,\sinh\eta)$$

where $\alpha(t) = t/Ro$ is the angle of attack and $Ro = U/\Omega a$ is the Rossby number with Ω the angular velocity of the tip of the ellipse.

The above problem was solved numerically on a grid of 97 x 96 points. The choice of reference frames and the details of the numerical results are presented by Lugt and Ohring [17]. One of the computer-plotted pictures of the streamlines and vorticity lines included in this reference, obtained for the case Re = 200 and Ro = 0.5, is shown in Figure 5. In this figure the coordinate reference frame is fixed to the body with regard to translation, but the body rotates relative to this reference frame. This time sequence occurred during the fourth revolution of the body. Such pictures are useful for analyzing the complex flow fields generated by the interference of the plate with the shed vortices as the plate continues to rotate. The computer program, ROTAPLATE, developed by Lugt and Ohring to perform these sophisticated calculations, requires less than an hour of computing time on an IBM 360-91 for each complete revolution. Such speed was made possible only by the use of the fast direct

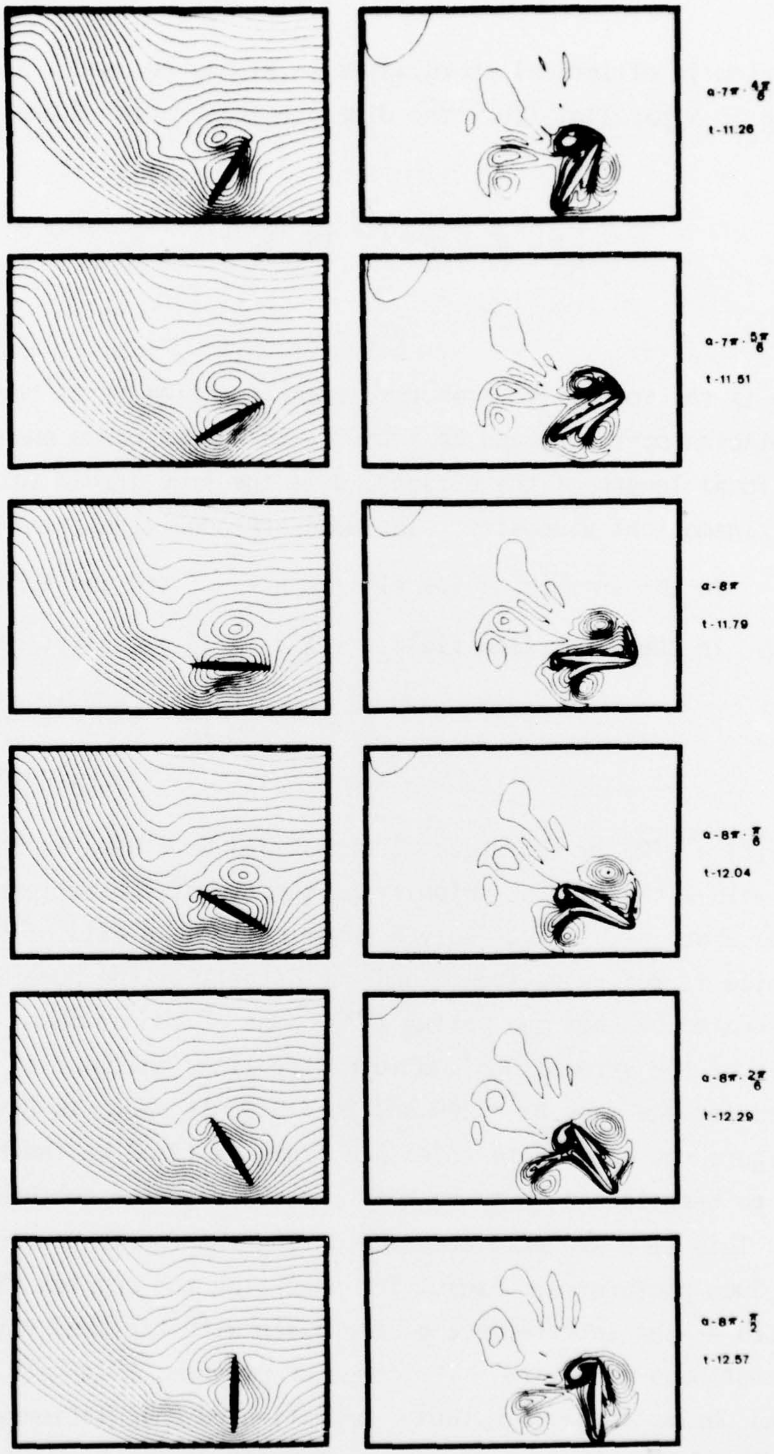

Figure 5. A Time-Sequence of Streamlines and Lines of Constant Vorticity for an Elliptical Cylinder Rotating in a Parallel Stream with Re = 200 and Ro = 0.5. The angle of attack α is indicated for the various time values.

Poisson solver based on Hockney's method. This program is therefore a powerful computational tool for investigating the phenomenon of autorotation and for calculating aerodynamic noise.

4. Fluid-Structure Interactions

The flow problems discussed in the foregoing sections were formulated under the assumption that the solid bodies remain undeformed by the actions of the surrounding fluid. There are many types of problems in which interactions between the fluid and the solid body must be taken into account. Those of naval importance include, for example, flow-induced vibrations, ship silencing, and shock response of ships and other structures. At the Center efforts are underway to develop improved formulations and solutions of fluid-structure interaction problems. Progress can already be cited in the dynamic analysis of submerged structures.

A method which uses standard versions of NASTRAN [18], [19], [20] for the calculations has been developed by Everstine and others [21], [22] for determining the transient response of a ring-stiffened cylinder to an underwater nuclear blast. A finite-element approach is used to model the cylinder in an acoustic medium which is assumed to be initially stationary. The fluid is assumed to be compressible and inviscid, with the pressure p satisfying the wave equation

$$\nabla^2 p = \frac{1}{c^2} \frac{\partial^2 p}{\partial t^2} \tag{10}$$

The boundary conditions at the fluid-structure interface may be specified by

$$\frac{\partial p}{\partial n} = - \rho \frac{\partial^2 u_n}{\partial t^2} \tag{11}$$

where n is the outward normal from the solid at the fluid-solid interface, ρ is the fluid mass density, and u_n is the normal component of the displacement. At rigid walls, equation (11) reduces to $(\partial p/\partial n) = 0$. At a free surface, in the absence of waves, the boundary condition is given by $p = 0$. In the above notation, t is the time and ∇^2 the Laplace operator.

In this particular formulation the fluid effects can be treated using an approximation which mathematically uncouples the structural response

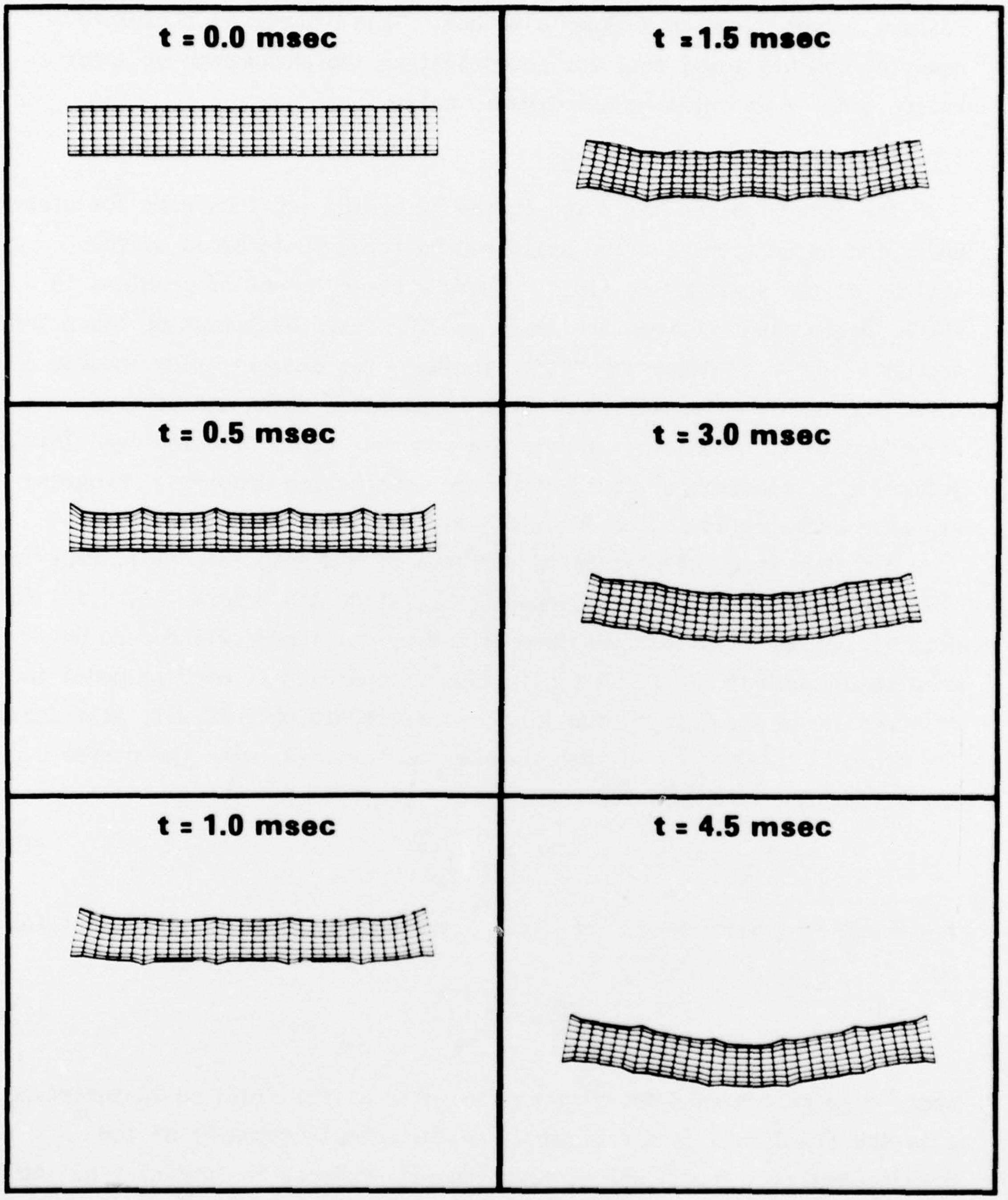

Figure 6. Time Sequence of the Response of a Submerged Ring-Stiffened Cylinder to Shock Wave from a Nuclear Blast. The direction of the shock wave is from the top of the page to the bottom.

from the fluid in the sense that the fluid pressure at the fluid-solid interface is determined only from the motion of the solid surface. References [21] and [22] provide the details of the numerical calculations. Figure 6 illustrates a time-sequence of the results obtained with the decoupling approximation. In this figure the shock wave from the nuclear blast is moving from the top of the page downward past the circular cylinder. Each rectangle after time t = 0.0 sec shows the effect of the blast on the rigid-body displacement and the elastic deformation of the cylinder at an instant in time. The displacements are scaled by a factor of about 2500. The real time modeled in this calculation was 5 milliseconds which required about 45 minutes of computer time on the CDC 6600.

With the advancements being made in both finite-element and finite-difference techniques for solving fluid flow and structural analysis problems, improved methods for the study of fluid-solid interactions are being investigated. It is anticipated that this rather new area of research may have some impact on the future program of this Data Exchange Agreement.

Acknowledgments

It is with pleasure that I would like to thank Dr. Hans J. Lugt and the other authors whose work has been described in this paper for their valuable assistance.

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